Real plutonium.
Real experiments.
No nuclear yield.
Real important.

It's been nearly 22 years since the United States began its self-imposed moratorium on full-scale nuclear weapons tests, with the last one, Divider, occurring on September 23, 1992. While the moratorium has been strictly adhered to, the nation continues to conduct so-called subcritical tests, intended to help scientists determine the impact that old and aging plutonium will have on the U.S. nuclear stockpile. In the most recent subcritical test, Pollux, a hollow shell of plutonium was forced to implode, raising the plutonium's density until…um, that was it. Nothing else happened. Unlike a nuclear weapons test, a successful subcritical test ends without even a whimper, much less a nuclear bang.

"The device used in Pollux didn't contain enough plutonium to explode," explained Mike Furlanetto, the Diagnostic Coordinator for Pollux. "The test device couldn't reach a critical mass."

A critical mass is the minimum amount of nuclear material needed to realize a self-sustaining chain reaction, the process by which huge amounts of nuclear energy can be released. In a subcritical test, the plutonium mass is subcritical, and the plutonium density remains subcritical before, during, and after the test. A self-sustaining chain reaction isn't possible, and the entire experiment proceeds without generating any nuclear yield. As such, subcritical tests are allowed under the Comprehensive Test Ban Treaty, which bans all nuclear and nuclear test explosions.

Why spend time, effort, and millions of dollars to probe what amounts to a nuclear dud? It's because subcritical tests are currently the best and possibly only way to obtain some of the data needed to validate weapons simulations—the extremely sophisticated supercomputer programs used to assess the weapons in the U.S. nuclear stockpile. In the

absence of nuclear testing, the nonnuclear subcritical tests are crucial for helping the nation maintain a stockpile that is safe and performs as required long into the future.

This is a test

What transpires within a detonated weapon is so complicated and dynamic that as of today, nearly 70 years after the first nuclear device melted the pale desert sand southeast of Socorro, New Mexico, scientists still can't fully describe what happens. Temperatures and pressures inside the weapon soar to extreme values on very short timescales, giving strength to non-linear, turbulent, and non-equilibrium behavior in materials and energy fields. The dynamic behavior of plutonium under such extreme conditions is largely unknown, as is its equation of state—the relationship that, given information about the its volume, pressure, and temperature, would allow one to calculate its density. Consequently, it's not clear what the state of the plutonium is in the crucial last moments when the chain reaction unleashes over 90 percent of the energy. Curiously, it's also not clear how the *initial* state of the plutonium works its way into affecting weapons performance. But it does.

In the pre-moratorium past, such holes in the analytical framework could be ignored because beneath the curve of every question mark lay the capped bore hole from an underground nuclear test. A weapon's performance was determined by how much energy it yielded when detonated during a nuclear test. A weapons designer's intuition about a new weapon design was validated (or not) by a nuclear test. And the reasons why seemingly minor differences in a weapon's components—a change in the texture of the plutonium, for example—could negate a successful weapon design and turn boom to bust was to be explored and answered by one or more nuclear tests. But then all testing stopped.

Scientists today use supercomputers to step through and calculate what happens within a weapon from the moment it is triggered until it explodes. The key question is whether the weapons in our stockpile will perform as required—now, or at any time in the future. The question becomes more relevant the longer a weapon stays in service, given a weapon's sensitivity to changes and the fact that plutonium slowly changes over time due to radioactive decay and the accumulation of decay products. The weapon itself may slowly change over the years as well, as parts get refurbished, remanufactured, or replaced.

Whether a simulation can predict performance depends on how faithfully the simulation reproduces what happens within the weapon. Scientists have a good understanding of the physical processes that take place, but they have only a sketchy feel for how some of those processes feed back,

The Castor subcritical test imploded a tantalum shell as preparation for the Pollux experiment. The test device was placed within the containment vessel shown.

compete with, or complement each other. Whether the simulation sufficiently captures the full dynamic interplay can only be determined by comparing the simulation results with data from an experiment and, in particular, with the data from a subcritical test.

A total of 27 subcritical tests have been performed since 1992. Pollux was notable in that the test device was a scaled-down version of a weapon component. It also fielded a new diagnostic: multiplexed photonic Doppler velocimetry (MPDV). Developed through a partnership between Los Alamos and National Security Technologies, LLC (NSTec), the MPDV system gathered so much high-quality data that scientists are already gaining new insight into plutonium's behavior under extreme conditions.

Nuclear chain reaction

Almost all modern nuclear weapons are staged explosives consisting of two nuclear devices—a primary and a secondary—sealed together in a case but separated from each other. The primary, detonated first as its name suggests, generates the energy needed to ignite the secondary, the device that produces most of the weapon's explosive power.

Both the primary and secondary derive the bulk of their power from nuclear fission, the process whereby the nucleus of a heavy atom, such as plutonium or uranium, absorbs a neutron and splits into typically two pieces. Fission releases a relatively huge amount of energy—on the order of 10 million times that gained by breaking a chemical bond—and also lets loose a few neutrons, the latter fleeing the ruptured nucleus like birds from a broken cage.

The extra neutrons are significant because each has the potential to be absorbed and induce fission in another nucleus, spawning a second generation of neutrons, which can then lead to a third generation, and so on in what is called a chain reaction. If every fission event produced two neutrons, and if each of those neutrons induced a fission event that produced two neutrons, then the number of fissions and neutrons increases exponentially with each generation.

The chain reaction is hard to achieve, however, because the uncharged neutrons are rather ephemeral particles, more likely to pass right through even a large piece of plutonium than to be absorbed. For any finite amount of material, one can calculate the rate at which neutrons leak from the surface. It will depend on the density of the piece, its shape, its purity, whether surrounding materials reflect neutrons back into the piece, and other factors. One can also calculate the rate at which neutrons are produced, which also depends on several factors, including the fission rate, and the number of neutrons produced per fission.

Equating the two rates provides a condition of criticality, which can be solved to derive a critical density. Knowing then the shape and volume of the piece, one can obtain the critical mass—the minimum amount of material needed to have one neutron, on average, induce just one other fission. If a critical mass is shrunk in size, thereby increasing its density, the plutonium becomes supercritical—fissions increase exponentially with each generation—whereas making the piece larger makes it subcritical—neutrons are lost faster than fission can replace them, and the nuclear chain reaction can't be sustained.

A weapon at work

Keeping a weapon safe has led to a primary design in which a thick layer of high explosive surrounds a hollow core made of plutonium. There's enough material that, if the core were smaller, the plutonium would reach critical mass. Because the material is formed into a hollow shell, the core density is subcritical and the weapon can't explode.

When the weapon is triggered, however, detonators on the surface ignite a thin layer of the explosive, launching a shockwave of intense temperature and pressure that races towards the core at several thousand meters per second. Self-powered by burning the material it overruns, the shockwave

Generation 1 2 3 4 5 10 20 30 50 100

slams into the core with enough force to level a small building, causing it to implode, or collapse smoothly in on itself. As the shell diameter shrinks, the plutonium reaches first critical and then supercritical density. Any fission that occurs within the plutonium at this point will initiate a supercritical chain reaction, so a hail of neutrons generated by a component external to the primary are fired at the super-dense nuclear fuel. Multiple fissions occur, jump starting the awesome energy-releasing chain reaction.

In less than a millionth of a second, the released energy is large enough to reverse the implosion and begins to blow the primary apart. The primary is by then so hot that it radiates most of its energy away as x-rays. For a brief amount of time, the weapon's outer case is able to contain the horrifically hot emissions, and radiation flows to the secondary. The radiation exerts enough pressure to compress the secondary, instigating nuclear reactions and a second supercritical chain reaction that produces the bulk of the weapon's nuclear yield.

Of the two devices, the primary is far and away the more finicky. If the primary does its job, the secondary will ignite and do its job. But there are myriad ways for the primary to fail, including mistiming events such that the supercritical state is never achieved, is reached too quickly, or isn't sustained long enough to produce the desired primary yield. The shockwave may not have sufficient energy, or it could converge non-uniformly on the plutonium shell. Its impact with the metal is violent, and the plutonium can crack, or chunks can spall from its surface. It will heat up, frantically rearrange its atoms, and flow like super-dense water in response to the unyielding pressure.

Do these physical processes affect the amount of energy produced? They do. By how much? That depends on numerous factors, including the response of the metal to the stress—its hydrodynamics—and the density of the shocked metal as determined by plutonium's equation of state.

Los Alamos weapons designer Gary Wall, the lead designer of seven nuclear tests and one of the few people around who has actually participated in a nuclear test, speaking publicly stressed that, "the greatest single technical challenge of primary design and assessment today is understanding and modeling the dynamic behavior of plutonium over a wide range of temperature and pressure."

The subcritical test allows scientists to study the plutonium under conditions similar to what it would experience in a weapon's primary. By measuring, for example, the velocity of the shell as a function of time, one can infer the force imparted to the shell by the shock wave, or alternatively gain insight into plutonium hydrodynamics. As to whether another material could be studied instead, many feel the answer is no.

Says Furlanetto, "You can study surrogate materials and from that deduce how the plutonium will behave, but you won't know until you actually make the measurements on plutonium. Nothing behaves like plutonium except plutonium."

Going subcritical

The U1a complex lies some 300 meters beneath the dry desert sands of the Nevada National Security Site (NNSS), formerly known as the Nevada Test Site. It is a dense warren of sealable experimental chambers arranged in clusters, which connect to each other by several main tunnels, themselves connected to the surface by three vertical shafts. The tunnels are relatively spacious, with high ceilings and concrete floors; the experiment alcoves would likely feel roomy were they not crammed full of scientific instruments and equipment. The complex is where Los Alamos, Lawrence Livermore, and Sandia national laboratories collaborate with the National Nuclear Security Administration (NNSA), NSTec, and each other to conduct subcritical tests.

Number of neutrons available

2
4
8
16
32
1,024
1,048,576
1,073,741,824
1,125,899,906,842,624
1,267,650,600,228,229,401,496,703,205,376

Exponential growth proceeds frighteningly fast. If every fission produced two neutrons, and each neutron induced a fission, then the first generation of two neutrons produces a second generation with four neutrons, a third with eight, and so on. The numbers speak for themselves.

MultiplexPVD

Multiplexed photonic Doppler velocimetry (multiplexed PDV, or MPDV) can measure the velocity of a moving surface at many points simultaneously. Each of the more than 100 laser beams enters the probe via its own optical fiber, passes through a fish-eye lens, and is directed to a unique spot on a surface moving towards the probe. Some light is reflected straight back to the probe, through the lens and into the fiber. The frequency of this light is Doppler shifted, increased by an amount that depends on the velocity of the surface. It mixes with the outgoing laser light and generates a mixed wave whose amplitude varies (beats) at a frequency equal to the Doppler shift. Measuring the beat frequency yields the velocity.

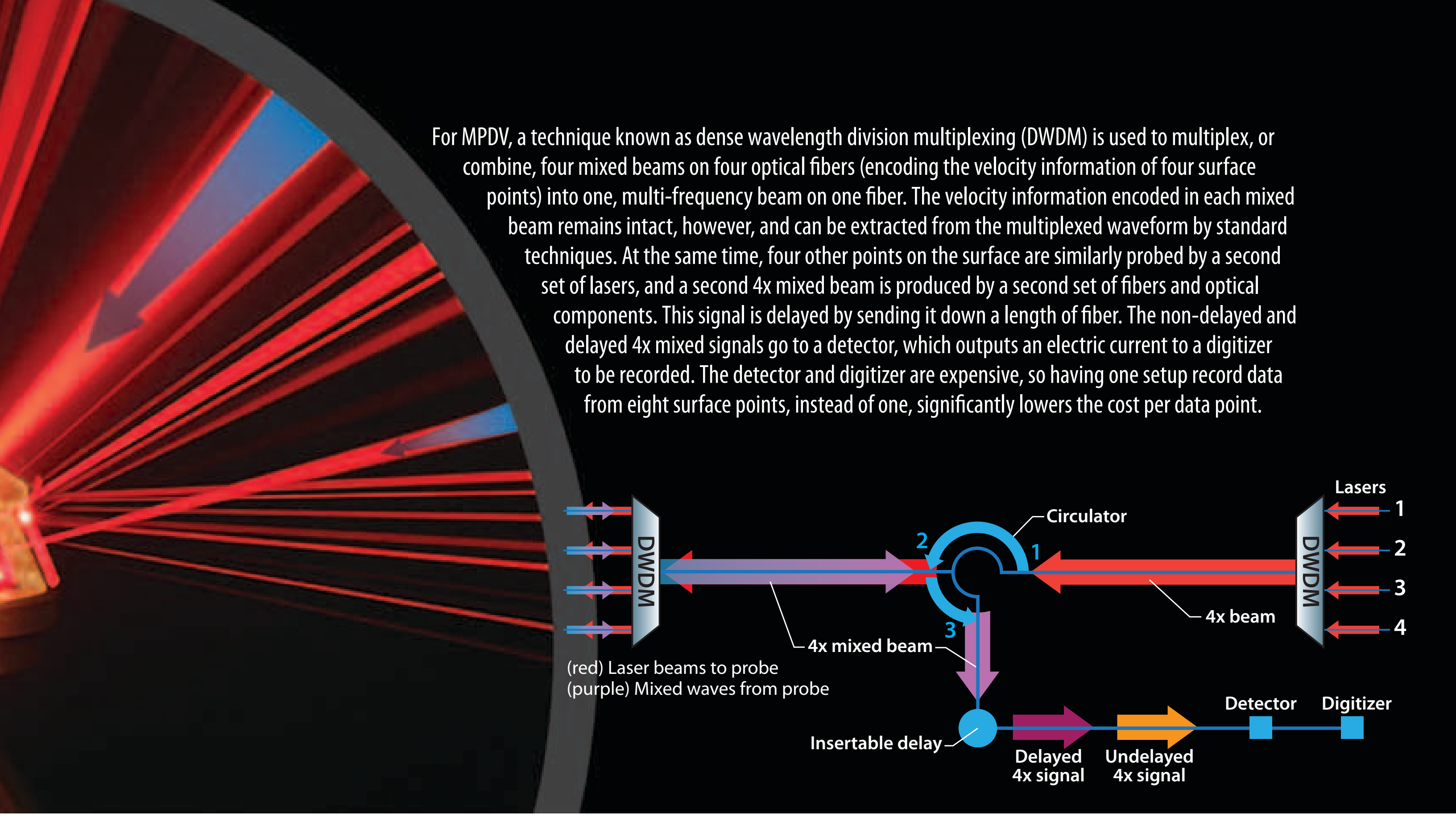
The two most recent tests, Castor and Pollux, comprised the Gemini experimental series, which was intended to get data on plutonium hydrodynamics as far into the implosion process as possible. Castor, the shakedown experiment, imploded a surrogate material. Pollux, fired on December 5, 2012, was the real deal, imploding a modified plutonium shell. Both experiments fielded test devices that were scaled-down versions of a primary.

The run-up to Pollux was watched with great interest by the weapons and shock-physics communities because the new MPDV diagnostic would be deployed to measure the velocity of the plutonium shell as it imploded. The instrument added a big M (for multiplexed) to photonic Doppler velocimetry (PDV), which was developed nearly ten years ago by Ted Strand and colleagues at Lawrence Livermore National Laboratory.

The frequency of laser light reflected off a moving object is shifted by an amount that depends on the object's velocity. By applying a wave mixing technique used in telecommunications, the velocity can be extracted using proven data analysis techniques. The PDV system, built entirely with fiber optics and standard optical components, proved to be robust, easy to align, and accurate; and given that the necessary optical components had been developed by the telecommunications industry and were commercially available, it could be built and operated on the cheap. The shock-physics community loved it.

The weapons community wanted more than a single probe, however. In particular, they wanted to look at the symmetry of the shell as it imploded, and so desired simultaneous velocity measurements from 100 or more places on the shell. But while one PDV channel was very cost-effective compared to the technology that it replaced, the 25 high-speed digitizers needed to process the minimum of 100 signals (four signals per digitizer) were priced at upwards of a prohibitive $4 million. In addition, each digitizer needed about a kilowatt worth of power, most of which got dumped into the room as heat. With 25 or more digitizers cranking away, the heat load in the U1a alcove would be difficult to manage.

The solution, developed through a collaborative partnership between Strand, Los Alamos physicist David Holtkamp, and Ed Daykin of NSTec, was to exploit even more what the telecommunications industry had already developed and use both frequency- and time-multiplexing techniques to combine eight PDV channels into a single complex signal that could be recorded by one digitizer channel. The result was a five-fold reduction in the cost per PDV channel and a roughly eight-fold reduction in the total heat load.



For MPDV, a technique known as dense wavelength division multiplexing (DWDM) is used to multiplex, or combine, four mixed beams on four optical fibers (encoding the velocity information of four surface points) into one, multi-frequency beam on one fiber. The velocity information encoded in each mixed beam remains intact, however, and can be extracted from the multiplexed waveform by standard techniques. At the same time, four other points on the surface are similarly probed by a second set of lasers, and a second 4x mixed beam is produced by a second set of fibers and optical components. This signal is delayed by sending it down a length of fiber. The non-delayed and delayed 4x mixed signals go to a detector, which outputs an electric current to a digitizer to be recorded. The detector and digitizer are expensive, so having one setup record data from eight surface points, instead of one, significantly lowers the cost per data point.

The system fielded on Pollux had a total processing capacity of 128 channels, with each channel requiring an independent laser beam. The beams were directed to spots on the inner surface of the plutonium shell by a special probe (above) designed by Brent Frogget and built by Vincent Romero, both of NSTec. During the Pollux test, this probe served double duty. The shell used in Pollux contained a subcritical mass of plutonium, even when imploded to its minimum size. But with the MPDV probe mounted inside, the shell could not implode completely—double insurance that the experiment remained subcritical.

Supercritical success

Holtkamp and his team fielded the system on the Pollux test. The system provided more than three million data points, vastly exceeding the sum of all such data gathered in previous subcritical experiments. He credits the team with the spectacular success.

"Working with such a talented and dedicated team has been the high point of my career," Holtkamp said. He remarked that the data "has had a revolutionary impact on the weapons program, reinvigorating Nevada activities and forging close collaborations between the design and experimental physics communities."

Gary Wall, commenting on the test results, noted that, "The additional constraints that [the data] put on the simulations are what I would call both exhilarating and frustrating. We typically find out that our simulations are just not up to the task, but that's what feeds back into improving our simulations."

And improving the simulations is what it's all about.

LDRD

—*Jay Schecker*

Jeff Hylok celebrates after the success of the Pollux subcritical test.